# Current and Position Sensor Fault Detection and Isolation for Driving Motor of In-wheel Independent Drive Electric Vehicle

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Abstract: This paper proposes model based current sensor and position sensor fault detection and isolation algorithm for driving motor of In-wheel independent drive electric vehicle. From low level perspective, fault diagnosis conducted and analysed to enhance robustness and stability. Composing state equation of interior permanent magnet synchronous motor (IPMSM), current sensor fault diagnosed with parity equation and position sensor fault diagnosed with sliding mode observer. Validation and usefulness of algorithm confirmed based on IPMSM fault occurrence simulation data.

## 1 INTRODUCTION

Driving motor for Electric car need to satisfy various requirements such as structural robustness, high output and torque, wide velocity, vibration, heat-proof, high efficiency driving control. IPMSM satisfy above requirements.

IPMSM is widely used in industries in behalf of induction motor because of higher output and efficiency than induction motor. Since IPMSM does not need field coil so rotor rotate same speed with stator magnetic field. There is no copper loss in IPMSM design, so IPMSM provide high peak efficiency compare to induction motor. Also power to weight ratio is higher that induction motor. With development of electricity and electronics, it is possible to apply IPMSM in high performance drive area.

Vector control is a way to control IPMSM precisely. Field oriented principle is used to control magnetic flux, space vector of current and voltage. Coordinate system that can separate vector to magnetic flux and torque occurrence is composed. To control magnetic flux and torque separately, need to dissociate stator current's magnetic field and torque occurrence part and compose a rotary coordinate system connected with rotor magnetic field. This is d-q coordinate system.

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To conduct vector oriented control, have to follow following procedure Measure of phase voltage and current, change measured data to 2-phase system ($\alpha$,$\beta$) with Clarke transformation, calculation of vector amplitude and position angle, change stator current to d, q-coordinate with Park transformation, stator current torque and magnetic field is controlled, output stator voltage space vector is calculated using decoupling block, changing stator voltage space vector from d, q coordinate to 2-phase coordinate related with stator with iPark transformation, generation of 3-phase voltage with sine wave modulation.

Since driving motor of in-wheel independent drive electric vehicle is in wheel, many surroundings such as physical shock, temperature and humidity change can cause fault. For stability of vehicle, it need to diagnosis fault fast and effective and.

There are two ways of fault diagnosis method. One is Hardware redundancy and another is analytic redundancy. Hardware redundancy is using same sensor or actuator that can replace fault part. It is easy to deal with fault but it need to pay more expense and assign space. Generally in vehicle, analytic redundancy is used considering system information and dynamics characteristic. This paper is using analytic redundancy to diagnosis fault.

In this paper, suppose that there are fault in measurement of current sensor and positon sensor. To isolation and diagnosis the fault, modelling of the



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IPMSM is introduced, model based fault detection and isolation (FDI) is proposed, types of current and position sensor faults are introduced. Finally, simulation results for validation of proposed FDI algorithm.

# 2 FAULT DIAGNOSIS

## 2.1 IPMSM Model

Fig. 1 express d-q equivalent circuit of IPMSM and Equation1 express voltage equation of d-q rotary coordinate system.

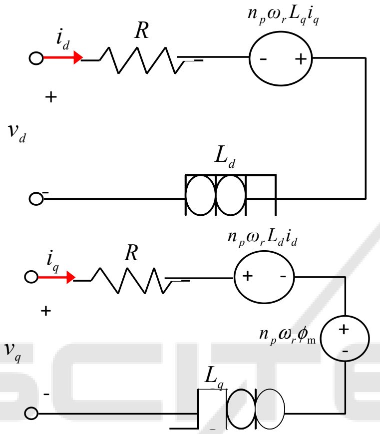


Figure 1: D-q equivalent circuit for IPMSM.

$$\begin{aligned} v_d &= Ri_d + L_d\frac{di_d}{dt} - n_p w_r L_q i_q \\ v_q &= Ri_q + L_q\frac{di_q}{dt} + n_p w_r L_d i_d + n_p w_r \phi_m \end{aligned} \tag{1}$$

$v_d$, $v_q$ are the d-q axes applied voltages.

$i_d$, $i_q$ are the d-q axes currents, $w_r$ is the rotor speed, R is the armature winding resistance, $L_d$, $L_q$ are the d-q axes inductances, $\phi_m$ is the magnet flux linkage.

Equation (2) is transformation from 3-pahse fixed coordinate system to 2-pahse rotary coordinate system.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

Most cases in 3-phase motor system use 2-phase current sensor does not use 3-phase current sensor because it costs more. Using motor current equivalent $i_a + i_b + i_c = 0$, we can eliminate $i_c$ in equation (2).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{3} & \frac{2\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{3}$$

## 2.2 Current & Position Sensor Fault Diagnosis

It is possible to fault diagnosis of current and position sensor of IPMSM using parity equations.

### 2.2.1 Current Sensor Fault Diagnosis

To compose parity equation, state space equation is following.

$$\begin{aligned} \dot{x} &= \mathrm{A}x + \mathrm{B}u + \mathrm{E_x}\, d \\ y &= \mathrm{C}x + \mathrm{D}u + \mathrm{E_y}\, d + \mathrm{F_y}\, f \end{aligned} \tag{4}$$

Where x∈$R^n$ : state vector, u ∈ $R^m$ : the vector of measured input signals, y ∈ $R^P$ : the vector of measured plant output signals, d ∈ $R^{n_d}$, f ∈ $R^{n_f}$ : the vectors of unknown input signals, f : the faults one wishes to detect, $d$ : unknown disturbances.

We express equation (4) as transfer function, following is expressed.

$$\begin{aligned} y(s) &= H_{yu}(s)u(s) + H_{yx}(s)x(0) \\ &\quad + H_{yd}(s)d(s) + H_{yf}(s)f(s) \\ &\begin{cases} H_{yu}(s) = C(sI-A)^{-1}B + D \\ H_{yx}(s) = C(sI-A)^{-1} \\ H_{yd}(s) = C(sI-A)^{-1}E_x + E_y \\ H_{yf}(s) = C(sI-A)^{-1}F_x + F_y \end{cases} \end{aligned} \tag{5}$$

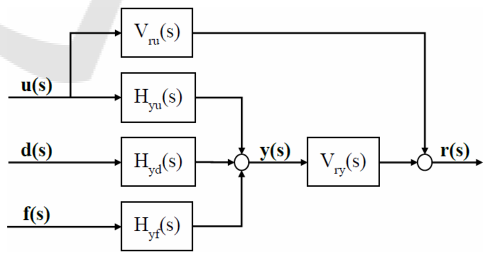


Figure 2: Structure of residual generator using parity equation.

By using Fig.2's residual, equation (6) follows.

$$\begin{aligned} r(s) &= V_{ru}(s)u(s) + V_{ry}(s)y(s) \\ &= V_{ru}(s)u(s) + V_{ry}(s)\begin{Bmatrix} H_{yu}(s)u(s) + H_{yd}(s)d(s) \\ + H_{yx}(s)x(0) + H_{yf}(s)f(s) \end{Bmatrix} \\ &= \begin{bmatrix} V_{ru}(s) + V_{ry}(s)H_{yu}(s) & V_{ry}(s)H_{yd}(s) \end{bmatrix} \begin{bmatrix} u(s) \\ d(s) \end{bmatrix} \\ &\quad + V_{ry}(s)H_{yx}(s)x(0) + V_{ry}(s)H_{yf}(s)f(s) \end{aligned} \tag{6}$$

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To affect by only fault signals, $\mathrm{u(s)}$ and $\mathrm{d(s)}$ 's coefficients must be 0. So we need to find $V_{ru}(s)$ and $V_{ry}(s)$ that satisfy.

$$\begin{bmatrix} V_{ry} & V_{ru} \end{bmatrix} \begin{bmatrix} H_{yu} & H_{yd} \\ I & 0 \end{bmatrix} = 0 \tag{7}$$

In this way, state space equating expressed as follows.

$$\begin{aligned}
&\dot{x} = \mathrm{A}\,x + \mathrm{B}u + \mathrm{E_x}\,d \\
&y = \mathrm{C}\,x + \mathrm{D}u + \mathrm{E_y}\,d + \mathrm{F_y}\,f \\
&x = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, u = \begin{bmatrix} v_d \\ v_q - n_p \omega_r \phi_m \end{bmatrix}, y = \begin{bmatrix} i_a \\ i_b \end{bmatrix}, f = \begin{bmatrix} i_{a_f} \\ i_{b_f} \end{bmatrix} \\
&\mathrm{A} = \begin{bmatrix} -\dfrac{R}{L_d} & \dfrac{n_p \omega_r L_q}{L_d} \\ -\dfrac{n_p \omega_r L_d}{L_q} & -\dfrac{R}{L_q} \end{bmatrix}, \mathrm{B} = \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \end{bmatrix} \\
&\mathrm{C} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix}, D = 0 \\
&\mathrm{F_y} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix}
\end{aligned} \tag{8}$$

We considered only sensor faults ( $F_x = 0$ ) and disturbance is neglectful ($E_x = E_y = 0$).

Let $w_r$ is pseudo constant[5] and change equation (8) to transfer function like equation (5)

$$\begin{aligned}
&H_{yu}(s) = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix} \dfrac{1}{K} \begin{bmatrix} R + sL_q & n_p \omega_r L_q \\ -n_p \omega_r L_d & R + sL_q \end{bmatrix} \\
&H_{yd}(s) = 0
\end{aligned} \tag{9}$$

Where $\mathrm{K} = (\mathrm{R} + \mathrm{s}L_d)(R + sL_q) + n_p^2 w_r^2 L_d L_q$

Applying Equation (9) to Equation (7), can calculate $V_{ry}(s)$ and $V_{ru}(s)$.

$$\begin{aligned}
&V_{ry}(s) = \begin{bmatrix} -n_p \omega_r L_d & -R - sL_q \\ -R - sL_d & n_p \omega_r L_q \end{bmatrix} \\
&V_{ru}(s) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}
\end{aligned} \tag{10}$$

So residual is following,

$$\begin{aligned}
\mathrm{r(s)} &= \mathrm{V_{ry}(s)y(s)} + \mathrm{V_{ru}(s)u(s)} \\
&= \begin{bmatrix} -n_p \omega_r L_d & -R - sL_q \\ -R - sL_d & n_p \omega_r L_q \end{bmatrix} \mathrm{y(s)} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \mathrm{u(s)} \\
&= \begin{bmatrix} -n_p \omega_r L_d & -R - sL_q \\ -R - sL_d & n_p \omega_r L_q \end{bmatrix} \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix} f(s)
\end{aligned} \tag{11}$$

Now, we make a coordinate transformation to separate current sensor faults in a, b phase.

$$\begin{aligned}
\mathrm{r'(s)} &= \left( \begin{bmatrix} -n_p \omega_r L_d & -R - sL_q \\ -R - sL_d & n_p \omega_r L_q \end{bmatrix} \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix} \right)^{-1} \mathrm{r(s)} \\
&= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} f(s) \\
&= \begin{bmatrix} r_1 \\ r_2 \end{bmatrix}
\end{aligned} \tag{12}$$

From equation 12, residual $r_1$ and $r_2$ affected by $i_{a\_f}$ and $i_{b\_f}$ independently.

### 2.2.2 Position Sensor Fault Diagnosis

Above fault diagnosis algorithm consider only current sensor fault. To confirm separation possibility of fault isolation, we need to analysis correlation with each sensor.

From equation (13) and (14), we can express sensor information that affect $r_1$ and $r_2$ following.

$$r_5 : 0 = r_5(v_d, v_q, i_a, \theta) \tag{13}$$

$$r_6 : 0 = r_6(v_d, v_q, i_b, \theta) \tag{14}$$

We can express $r_1$ and $r_2$ as fault table.

Table 1: Fault table of fault diagnosis residual.

| | $v_d$ | $v_q$ | $i_a$ | $i_b$ | θ |
|---|---|---|---|---|---|
| $r_1$ | X | X | X | | X |
| $r_2$ | X | X | | X | X |

X in Table 1 means relation with residual $r_i$(i = 1,2) and fault of each sensor. If we assume single fault of system, it is possible that fault is separable of current sensor $i_a, i_b$ and position sensor θ through $r_1$ and $r_2$.

## 3 SIMULATION RESULTS

Suggested algorithm realized with Matlab/Simulink. IPMSM control system was selected as AC6 - 100 kW Interior Permanent Magnet Synchronous Motor Drive in example of Matlab/Simulink. Parameter of motor model is following in Table 2.

Table 2: IPMSM model parameter.

| Parameter Name | Value (Unit) |
|---|---|
| Stator resistance (R) | 8.296 (mΩ) |
| d-axis stator inductance ($L_d$) | 0.174 (mH) |
| q-axis stator inductance($L_q$) | 0.293 (mH) |
| Magnet flux linkage($\emptyset_m$) | 71.115 (mV · s) |
| Inertia( $J$ ) | 0.089 (kg · $m^2$) |
| Viscous damping( $F$ ) | 0.005 (Nm · s) |
| Pole pairs( $n_p$ ) | 4 |

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Figure 3 is fault command to each sensor. From 0.5s to 0.7s fault signal to current sensor of phase a adding 100A offset, from 1s to 1.2s fault signal to current sensor of phase b multiplying gain 2 and from 1.5s to 1.7s fault signal to position sensor adding 0.1 rad offset.

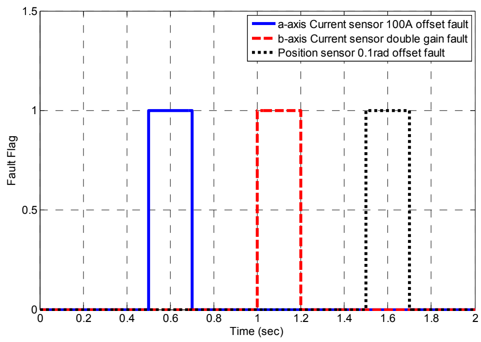
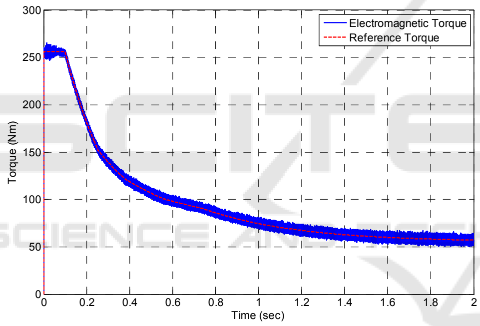
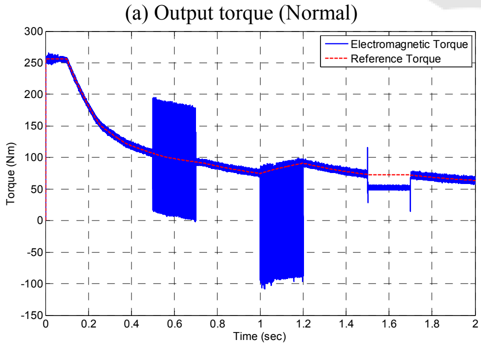



Figure 3: Torque control simulation results (Fault flag).

Figure 4 shows electromagnetic torque of IPMSM control system respect to reference torque.



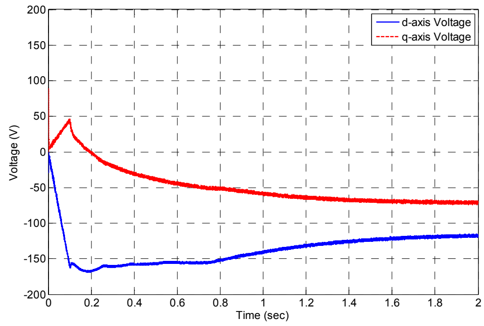

(a) Output torque (Normal)



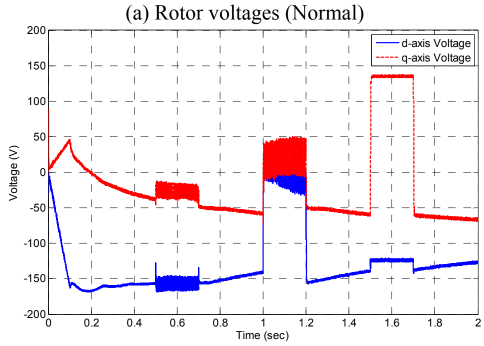

(b) Output torque (faulty)

Figure 4: Torque control simulation results (Output Torque).

Figure 5 shows d-q axis input voltage of IPMSM control system.



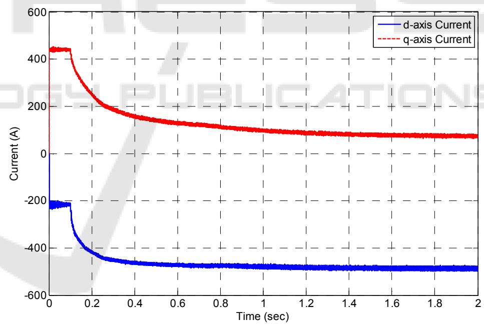

(a) Rotor voltages (Normal)



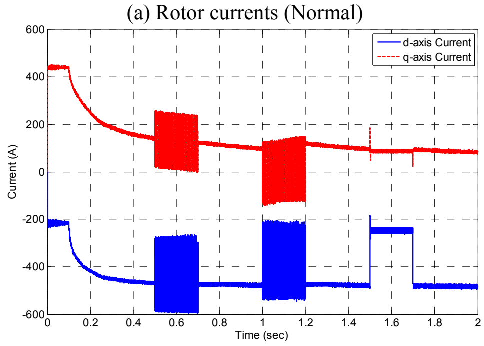

(b) Rotor voltages (faulty)

Figure 5: Torque control simulation results (Input voltage).

Figure 6 shows d-q axis current of IPMSM control system.




(a) Rotor currents (Normal)




(b) Rotor currents (faulty)

Figure 6: Torque control simulation results (Rotor currents).

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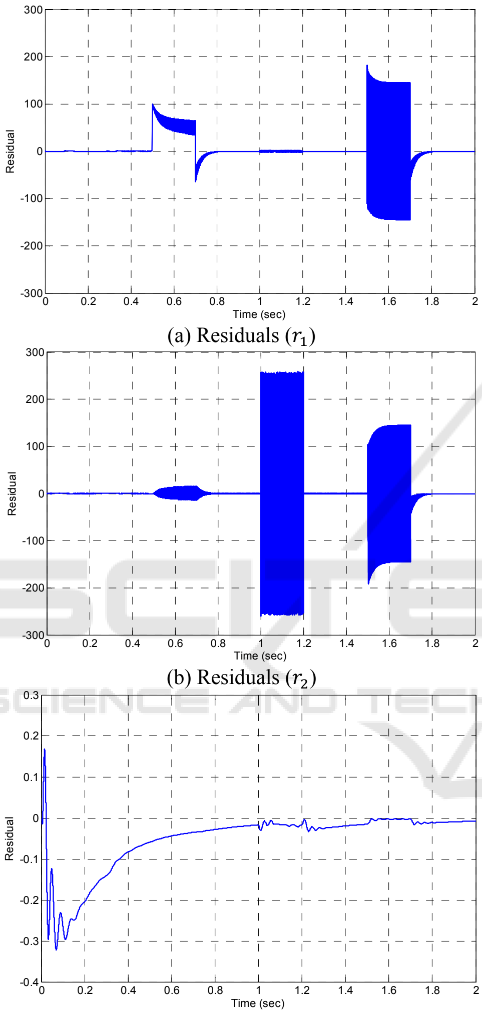
From simulation results, when current and positon sensor break down, it affects electromagnetic torque, input voltage and current. It can be identified that fault of one part can affect different parts in control system.

Figure 7 shows proposed algorithm$r_1$, $r_2$ and $r_3$ in fault situation.




(a) Residuals ($r_1$)

(b) Residuals ($r_2$)

(C) Residuals ($r_3$)

Figure 7: Torque control simulation results (Input voltage).

In Figure 7, like Table 1's fault table, when current sensor of phase a breakdown $r_1$ breaks away from 0 a lot and when positon sensor break down both $r_1$ and $r_2$ breaks away from 0 a lot. In case of $r_3$, since position estimation's response is slow so that insensitive to fault, it does not react that much to the fault. However assume only single fault, it can be fault diagnosis and isolation through residual $r_1$ and $r_2$.

## 4 CONCLUSIONS

In this paper, current and position sensor fault detection and isolation algorithm suggested and we confirmed validation with simulation results. This fault diagnosis method can be applied to In-wheel independent drive electric vehicle but also it is possible to apply and extend to other subsystems. We expect that proposed fault diagnosis algorithm can develop robustness and stability of electric vehicle system.

In further study, we will conduct experiment this system with motor test bench. We hope that we can obtain same result with proposed fault diagnosis and isolation algorithm with parity equations.

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